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Our major research breakthroughs to date include:

- Developing and operating a novel, multi-sensored 'I'WI' for research of fundamental nonlinear physics in MPM-class TWTs, •Advancing a new understanding of the physics of nonlinear distortions in TWTs,
- Developing a new computational method to model ID linear-beam VEDs with Eulerian formulations, including the effects of charge overtaking, •Establishing the fundamental physical mechanisms of harmonic and distortion product injection for linearization of TWTs,
- Identifying a novel TWT transmitter configuration enabling extremely linear amplification of digitally-modulated signals while operating saturated and thus at maximum efficiency,
- Completing the first combined experimental and simulation study of impulse amplification in TWTs revealing realistic prospects for novel applications to impulse radar, impulse communications, and impulse response measurements of small signal gain characteristics,
- Conducting pioneering investigations of xray LIOA, UV LIGA and deep reactive ion etching methods for microfabricating mmwave and THz regime TWTs, and
- Developed and disseminated a suite of 1D TWT simulation codes for teaching and research of TWTs, making them available as open source software at http://www.lmsuite.or2.

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FINAL TECHNICAL PROGRESS REPORT

UNIVERSITY OF WISCONSIN-MADISON
AND
UNIVERSITY OF MICHIGAN – ANN ARBOR

"INVESTIGATIONS OF ADVANCED, SLOW-WAVE, MICROWAVE VACUUM ELECTRON DEVICES"

AFOSR GRANT F49620-00-1-0088

REPORT ON ACTIVITIES BETWEEN
AUGUST 1, 2000 THROUGH DECEMBER, 2004

PRINCIPAL INVESTIGATOR/POINT OF CONTACT:
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I. AFOSR FINAL REPORT: UNIVERSITY OF WISCONSIN-MADISON

I.1. Overview

During the five years of support from 1999 – 2004, the University of Wisconsin investigators made major research and education contributions in the following general categories:

- Multi-sensored TWTs for fundamental research of MPM-class TWTs
- Fundamental physics of nonlinear distortions in TWTs and klystron amplifiers
- Novel, improved methods for linearizing TWT and klystron amplifiers
- Microfabrication of mmwave and THz regime vacuum electronic amplifiers
- Novel operating modes of TWT amplifiers, including impulse amplification and chaos generation
- Fundamental physics of large-space-charge, MPM-class TWT amplifiers
- 1D TWT simulation codes for teaching and research of TWTs, available as open source software at http://www.lmsuite.org.
- Educated and trained 3 Ph.D., 1 post-doc, 12 M.S., and 11 B.S. students in microwave vacuum electronics.
- Published or submitted for publication 17 journal articles (with at least two more in preparation); presented 58 conference talks on subjects supported by the grant funds, including a Plenary Talk and an Invited Talk at the International Vacuum Electronics Conferences of 2002 and 2003, respectively.

Our major research breakthroughs to date include:

- Developing and operating a novel, multi-sensored TWT for research of fundamental nonlinear physics in MPM-class TWTs,
- Advancing a new understanding of the physics of nonlinear distortions in TWTs,
- Developing a new computational method to model 1D linear-beam VEDs with Eulerian formulations, including the effects of charge overtaking,
- Establishing the fundamental physical mechanisms of harmonic and distortion product injection for linearization of TWTs,
- Identifying a novel TWT transmitter configuration enabling extremely linear amplification of digitally-modulated signals while operating saturated and thus at maximum efficiency,
- Completing the first combined experimental and simulation study of impulse amplification in TWTs revealing realistic prospects for novel applications to impulse radar, impulse communications, and impulse response measurements of small signal gain characteristics,Conducting pioneering investigations of xray LIGA, UV LIGA and deep reactive ion etching methods for microfabricating mmwave and THz regime TWTs, andDeveloped and disseminated a suite of 1D TWT simulation codes for teaching and research of TWTs, making them available as open source software at http://www.lmsuite.org.

I.2. Significant Achievements

I.2.1. Multi-sensored TWT for nonlinear physics research in MPM-class TWTs

Microwave Power Modules are a revolutionary microwave power technology that exploit the best advantages of solid state and vacuum electronics. By sequencing a low power, high gain, low noise, solid state preamplifier with a high power, modest gain, very wideband TWT, along with innovative compact power supplies and thermal management design, the MPM provides the ultimate superior combination of efficiency, bandwidth, gain, power, and low noise in an incredibly compact package. MPMs owe a significant portion of their success to the innovation of MPM-class TWTs. While the gain is modest (20-30 dB), these TWTs are extremely compact, low voltage, have very wide bandwidths, and high efficiencies. To achieve the required gain in a short length results in typically high current and charge densities in the electron beam. This results in large values space charge and thus large values of the Pierce parameter QC. The combination of extra large bandwidth and large QC results in certain unique physical responses that are less well studied, but are very important for advancing MPMs for electronic warfare, radar, and communications. For example, control of harmonic distortion at the band edges is very important, as well as prospects for linear amplification of multiple carriers in multi-target ECM applications.

To learn more about the nonlinear physics of MPM-class TWTs, UW successfully collaborated with Northrop Grumman, to innovate, manufacture, and make operational a multi-sensored, MPM-class research TWT, referred to as the "XWING" (eXperimental WIsconsin Northrop Grumman) TWT, shown in Fig. 1, below. With these sensors we can measure the evolution of the circuit wave along the TWT, and even have the capability to directly measure the beam-modified ("hot") phase velocity of the wave, a fundamental physical parameter. This new TWT has been directly responsible for experimental verification of a new breakthrough on understanding nonlinear distortion mechanisms in TWTs, the first studies of impulse amplification in a wideband TWT, and the first direct experimental measurements of hot phase velocities in a high-space-charge, MPM-class TWT.

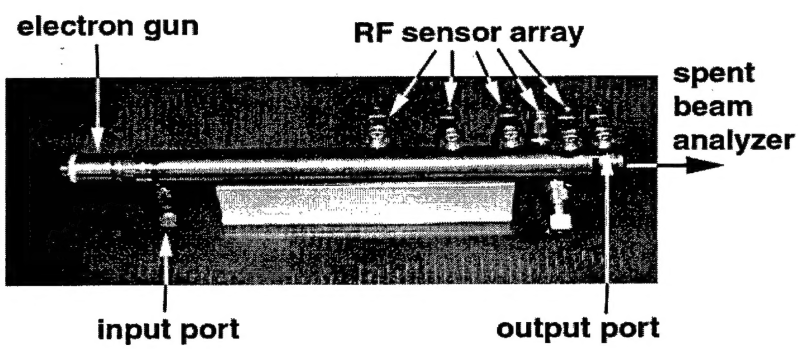

Fig. 1. Picture of the multi-sensored research "XWING" TWT, for fundamental research of nonlinear physics in MPM-class TWTs

I.2.2. The physics of nonlinear distortions in TWTs

Evolving communications systems need high data rates and high linearity, and make use of advanced modulation schemes. Evolving electronic warfare systems will require ultra-wide bandwidth and linearity at high power. Advanced radar transmitters envision multi-carrier operating modes for simultaneous tracking of multiple targets. Meanwhile, the traveling wave tube (TWT) amplifier has so many inherent performance advantages—bandwidth, compact power, efficiency, gain, and linearity--that it holds a dominating presence in most communications and electronic warfare systems as well as most compact radar on mobile platforms. Consequently, improving our fundamental understanding of nonlinear distortion mechanisms in TWTs can have a profound impact by pointing the way to more linear TWT amplifiers in radar, communications, and electronic warfare systems.

Our combined theoretical and experimental research has revealed a new way of understanding the nonlinear mechanisms behind fundamental and harmonic distortion in TWTs. In essence, all distortions associated with operation prior to saturation have their origin in spontaneous nonlinear second harmonic distortions on the electron beam that result from ballistic motion. All other distortions, including phase distortion at the fundamental, intermodulation distortion and higher harmonic distortion arise as intermodulation products from the second harmonic distortions on the electron beam.

In contrast to past models, this new model is quantitative and predictive, has a clearly understandable intuitive principle, and has been verified in comparisons of analytic theory and computation and experiment. It corrects a long-standing misconception that phase nonlinearity arises from slowing down of the electron beam and it provides a much firmer and clearer theoretical explanation for a recently invented method of TWT linearization [T. Chen, Y. Goren, et al, "A novel technology for linearizing traveling wave tube amplifiers, IEEE MTT-S I.M.Symposium Digest Cat No. 02CH37278, pp. 773-6, vol. 2 (2002).]. It has led to ideas for linearization using second harmonic injection that appear to have extremely high distortion suppression potential (see below and next section). Harmonic injection to suppress harmonic distortion and increase EW TWT bandwidths is clearly explained, and improved phase linearity using harmonic injection remains a possibility.

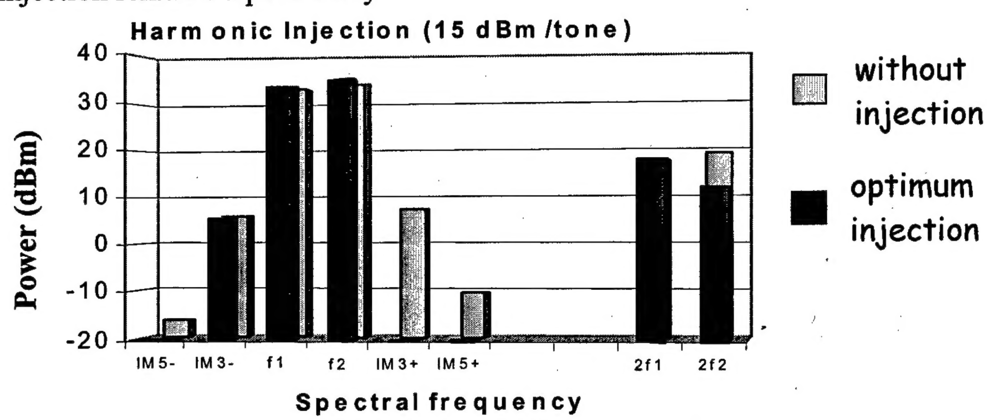

Fig. 2 Experimental verification of new nonlinear TWT theory explaining how harmonic injection suppresses 3rd and 5th order intermodulation distortions in two-tone operation.

I.2.3. Eulerian modeling of vacuum electron devices including charge overtaking

Advanced computer methods and hardware have contributed to the advancement of vacuum electronics technology by providing improved design codes as well as codes that lead to improved fundamental understanding of the complex physics. We have innovated a new method to model linear beam vacuum electron devices using an Eulerian formulation that accounts for particle overtaking. This new technique has been applied to and validated for klystron interactions. If applied to TWT modeling, it would enable substantially deeper insights and understanding of the complex nonlinear effects that occur when a TWT enters saturation. Moreover, the method has demonstrated dramatically greater computational speed than traditional Langrangian-type models.

It has long been understood that Eulerian (fluid-like) models provide extremely clear physical insight, but are unable to correctly model plasma, electron beam, and fluid systems when "wave-breaking" (particle overtaking) occurs. Lagrangian models use coordinate systems that are far less intuitive and therefore occasionally obscure the physical mechanisms of a phenomena. However, Lagrangian models have been powerful tools in vacuum electronics for their natural ability to handle charge overtaking phenomena that occur near saturation in TWTs, for example. We have innovated a new approach to Eulerian modeling that removes the many decades old barrier to accurately modelling charge overtaking. Our new method has been applied to modeling a klystron interaction with excellent agreement with the most exact models (e.g., kinetic theory). Moreover, the new method is dramatically faster than any alternatives and lends itself to clear intuitive physical insight regarding nonlinear mechanisms. (e.g., several days for Lagrangian vs. several minutes for Eulerian on a 1.8 GHz Gnu/Linux computer for a test case). The model is now being adopted for use in TWT simulations by Dr. J. Wöhlbier at Los Alamos National Laboratory.

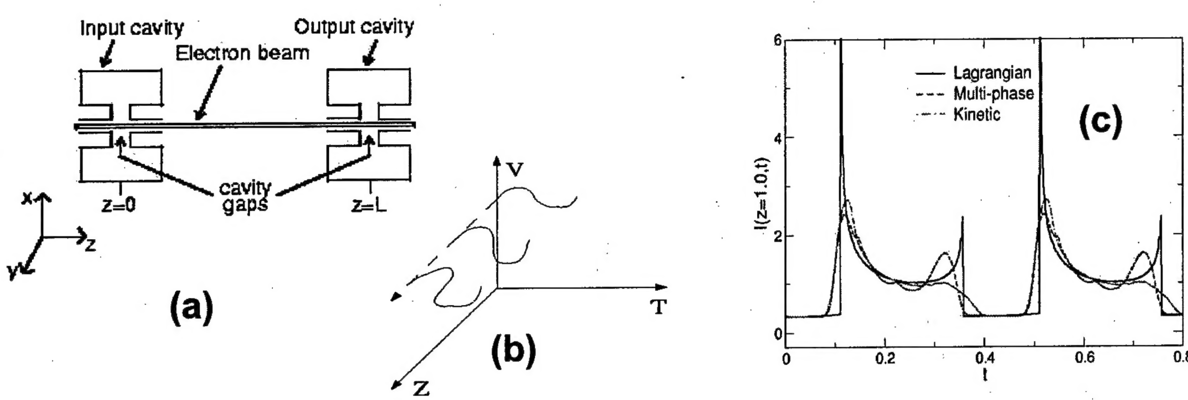

Fig. 3. Demonstration for a 1D Klystron of a new computational method for modeling VEDs with an Eulerian formulation, including charge overtaking. (a) schematic of the klystron, (b) illustration of how the fluid velocity becomes multivalued with charge overtaking, (c) comparison of a traditional Lagrangian, an "exact" kinetic, and the Eulerian ("multi-phase") calculation of the beam current versus time. The differences in (c) are primarily in the height,due to use of numerical viscosity in Eulerian and gaussians for delta boundary values in kinetic, but these distinctions have negligible effect on accurate prediction of output spectra. The Eulerian calculation was ~ 3 orders of magnitude faster than other computational methods.

I.2.4. The physics of harmonic and distortion product injection in TWT amplifiers

Evolving communications systems need high data rates and high linearity, and make use of advanced modulation schemes. Evolving electronic warfare systems will require ultra-wide bandwidth and linearity at high power. Advanced radar transmitters envision multi-carrier operating modes for simultaneous tracking of multiple targets. Meanwhile, the traveling wave tube (TWT) amplifier has so many inherent performance advantages—bandwidth, compact power, efficiency, gain, and linearity--that it holds a dominating presence in most communications and electronic warfare systems as well as most compact radar on mobile platforms. Consequently, improving our fundamental understanding of nonlinear distortion mechanisms in TWTs can have a profound impact by pointing the way to more linear TWT amplifiers in radar, communications, and electronic warfare systems.

We have developed a new description of harmonic (and other distortion product) injection that clearly reveals the underlying physics. Built upon the same general theoretical framework as our model for nonlinear distortions, our theory reveals that harmonic suppression results from destructive interference of two circuit voltage modes at the frequency to be cancelled, an injected mode and a nonlinearly generated mode. Contrary to previous hypotheses, the cancellation occurs only at one axial location. For linearization purposes, then, the objective is to tune the injected signal's amplitude and phase so that cancellation occurs at the tube output. Experiments (illustrated below) verify the theory as well as point out that suppression by as much as – 30 dB of harmonic and even intermodulation distortion components is achievable by proper selection of the injected signal parameters. The theory goes on to explain that concomitant increases of fundamental power seen when harmonics are suppressed is a result of constructive interference of two circuit modes at the fundamental frequency: the normal driven wave and a nonlinear mode resulting from intermodulation between the second harmonic and the fundamental excitations. Finally, the new understanding shows that injecting multiple tones (such as multiple harmonics, or second harmonic and intermodulation product frequencies) can provide even better methods for suppressing distortion products. However, the more tones one injects, the more complicated becomes the process of finding optimal injection parameters without worsening the distortion in some aspect of the output spectrum.

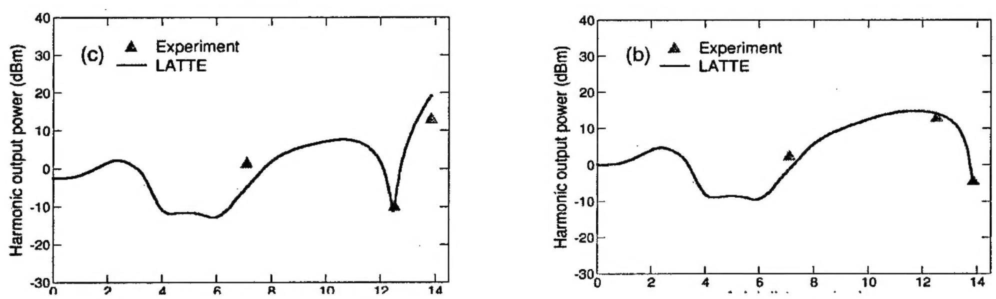

Fig. 4. Comparison of new nonlinear TWT theory with experiment explaining the physics of harmonic injection to suppress nonlinear distortion products. The new understanding is that the suppression results from destructive interference between two nonlinear modes in the voltage wave for the distortion product. Axial location of the suppression point depends upon the input power and phase of the injected harmonic signal.

I.2.5. LINC architecture for ultra-high efficiency linear transmitters of digitally modulated signals

Evolving communications systems need high data rates and high linearity, and make use of advanced modulation schemes. The most conventional method to minimize nonlinear distortion is to operate the transmitter's amplifier significantly below saturation, also called "backed-off" operation. However, operation at saturation provides maximum operating efficiency, while operating backed-off significantly reduces efficiency. The ideal situation is to realize an amplifier configuration with high linearity operating near or at saturation, and thus at peak efficiency. For TWT amplifiers the implication of such a configuration would be especially profound because of the extremely high efficiencies—between ~ 60 and 70 %—of a communications TWT operating near saturation.

Our research has identified a candidate configuration, called LINC, that would provide excellent TWT linearity at unprecendented operating efficiencies. Simulations based on DPQSK and similar modulation schemes common in North America indicate that spectral regrowth levels can be suppressed by –35 to -40 dB while operating the TWTs saturated. The LINC configuration (LINC stands for LInear amplification using Nonlinear Components) uses two TWT amplifiers, and special signal processing at the baseband to produce an unprecedented combination of linearity and efficiency. Figure 5(a) below is a block diagram of the architecture while Fig. 5(b) shows an illustration of the low-distortion amplified spectrum realized for saturated, maximum efficiency operation.

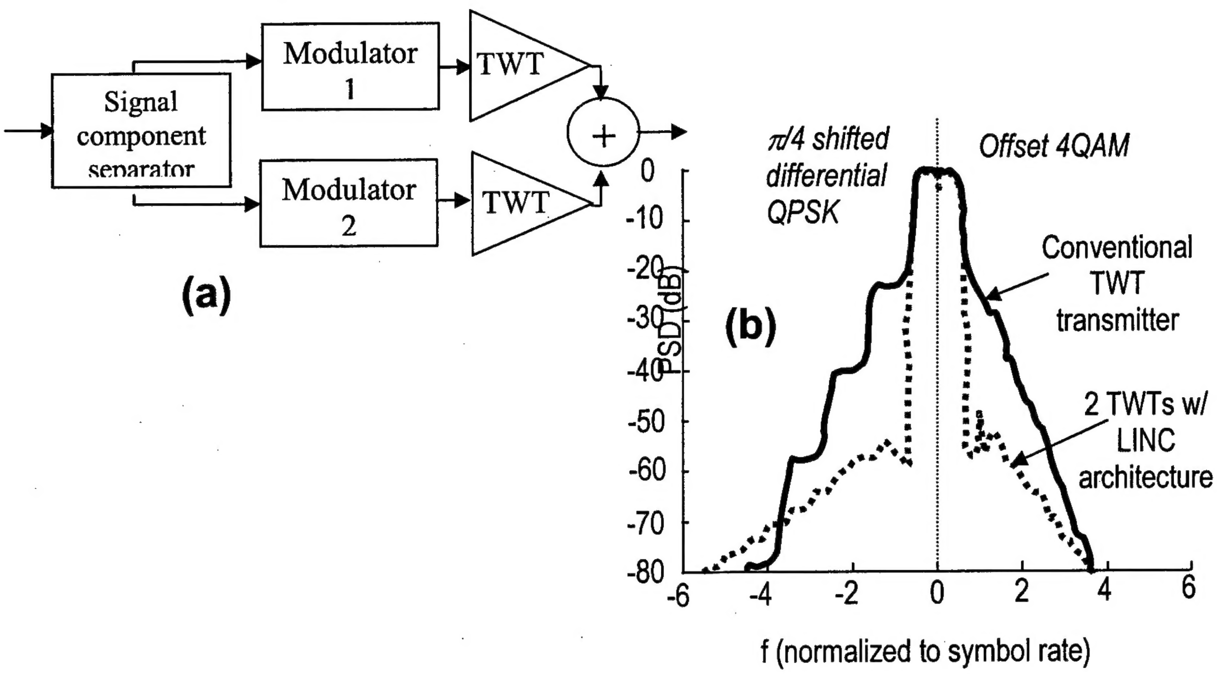

Fig. 5. TWT transmitter based on the LINC architecture (LInear amplification using Nonlinear Components). (a) LINC configuration. (b) illustrative output spectra of digitally modulated signals illustrating ~ -40 dB suppression of spectral regrowth from intermodulation distortion.

I.2.6. The physics of impulse amplification in wideband TWT amplifiers

The amplification of an impulse by a wideband TWT has several possible exciting applications. First, wideband TWTs could make an excellent amplifier in a communications link for impulse radio communications. Impulse radio techniques are highly spectrally efficient, robustly resistant to eavesdropping (ideal for secure covert communications) and resistant to multipath fading or jamming. High power impulse radar using a TWT would provide extremely high resolution, would be highly resistant to electronic counter measures, and would provide the exciting capability to "see through" obstructions such as walls, chaff, or earth. Finally, by analyzing the time-domain "impulse response" of a TWT, we can quickly, easily, and relatively cheaply obtain the entire small signal gain characteristics, as well as several interesting nonlinear characteristics from a single data "shot".

We have completed the first experimental and computational studies of the small and large signal amplification of ultra-wideband impulses in a wideband TWT. These studies identify the exciting capability of a TWT to amplify wideband pulses for applications such as impulse radio and radar. We have also confirmed that the small signal impulse response of a TWT provides provides the entire small signal gain versus frequency characteristics of a TWT quickly, easily, and inexpensively in a single data shot. Our studies suggest that a TWT can amplify a wideband impulse with very high gain and efficiency. The reason appears to be an absence of particle trapping with impulse amplification that typically causes saturation in more conventional, single frequency carrier amplification in a TWT.

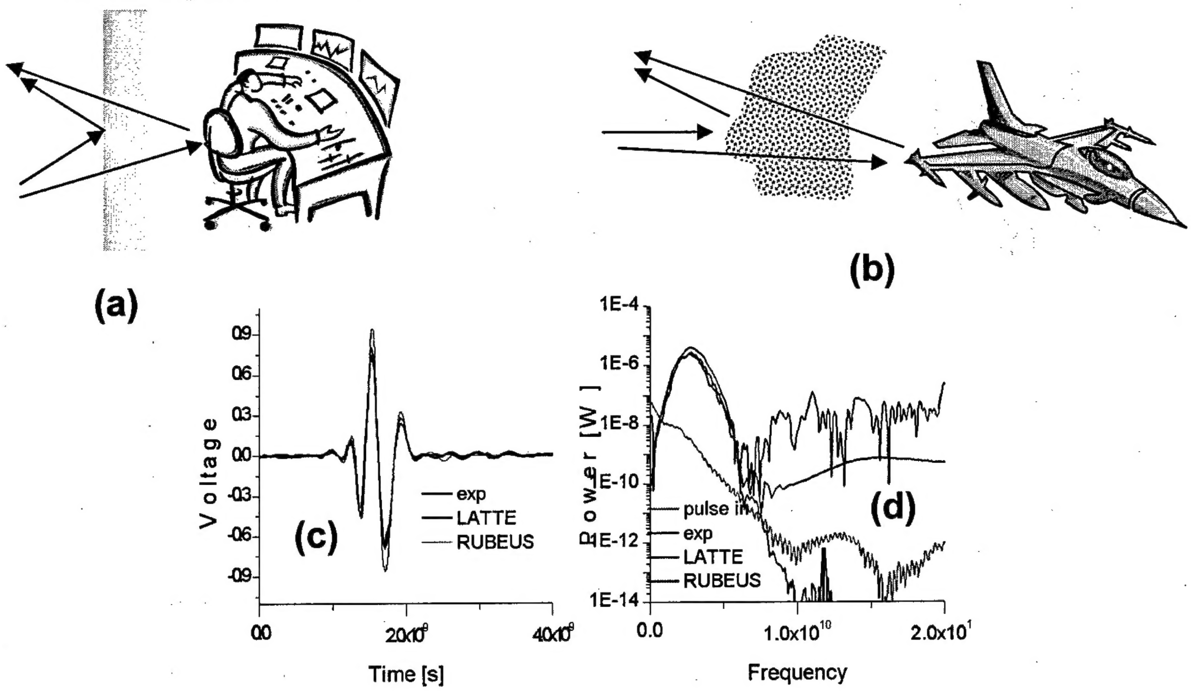

Fig. 6. Impulse amplification in wideband TWTs. Adapted for radar, one could obtain the ability to (a) conduct surveillance imaging through thick walls or (b) penetrate chaff countermeasures. In initial results good agreement between was realized between experimental measurements and computer predictions for impulse amplification in a wideband TWT, both in (c) output time-domain signal, and (d) output frequency spectrum

I.2.7. Microfabricated TWTs for advanced millimeter-wave and THz regime sources
Microfabrication techniques, born within the microelectronic integrated circuits industry and expanded and matured with the advent of MicroElectroMechanical Systems (MEMS) offers methods to fabricated small, sub-mm, electrical and mechanical components with high accuracy and precision, high yield, and potentially significant cost savings through batch production. Consequently, an ideal opportunity exists to marry some of the best aspects of solid state and vacuum electronics to realize low-cost, high-yield mm-wave to THz regime (100 – 3000 GHz) high power, compact sources. For mm-waves, application opportunities include close-in seeker radar, earth-space and space-space satellite communications, microsatellite cluster links, and high-data-rate wireless communications. For the THz regime (300-3000 GHz), there is a vast, untapped potential for extremely high-data-rate communications, advanced close-in radar, materials spectroscopy, space research, medicine, biology, surveillance, and remote sensing. The primary barrier to exploitation of this region of the spectrum remains the (lack of) availability of affordable compact sources (oscillators and amplifiers) of sufficient power. Vacuum electronic devices should theoretically be able to meet the needs of power and size. However,until now it has been prohibitively difficult to reliably fabricate the required small-dimensioned circuits and components.

We have conducted pioneering investigations of the applicability of modern microfabrication methods for mmwave and- THz regime TWTs. We have specifically focused on the folded waveguide (FWG) TWT as one whose circuit is naturally suited to planar microfabrication methods. To date, we have successfully demonstrated the feasibility of fabricating 400 GHz FWG TWT circuits using conventional xray LIGA, novel UV LIGA, and deep reactive ion etching (DRIE). Examples are shown below. The DRIE and UV LIGA approaches are especially attractive because they obviate the need for an xray synchrotron light source.

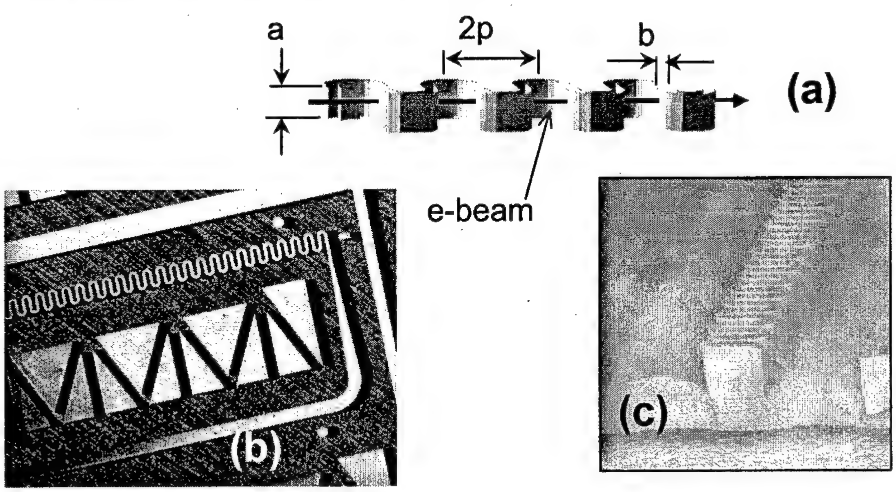

Fig. 7. Illustrations of fabrication of 400 GHz FWG TWTs using LIGA microfabrication methods. (a) basic configuration of a FWG TWT. (b) PMMA mold for a FWG TWT oscillator fabricated by xray LIGA. (c) SU-8 mold for a 400 Ghz FWG TWT circuit fabricated using UV exposure LIGA.

I.2.8. New open source simulation tools for TWT research and education

By virtue of their innate superior performance characteristics, traveling wave tubes (TWTs) hold a dominant position for microwave power amplifiers in radar, electronic warfare, and satellite communications applications. Evolving communications, radar, and electronic warfare systems require continuous improvements in transmitter technology to maintain technological superiority in the battlefield. There have been major advancements in bandwidth, linearity, frequency, efficiency, and size reduction in TWTs during the past 10 years, and there appears to be room for additional advances for several decades to come. There is both a need and an opportunity to realize these TWT technology improvements through basic university research and training of tomorrow's TWT design engineers. To that end, as a byproduct of our research on nonlinear distortion physics in TWTs, we have developed a suite of 1D TWT simulation codes that are ideal for teaching and basic research on TWTs. They are provided as open source software for all university, research laboratory or industrial scientists and engineers and can be downloaded from http://www.lmsuite.org. Over 38 user's from academia, government labs, and industry across the US and around the world have downloaded and used the codes for TWT research, education, and design studies.

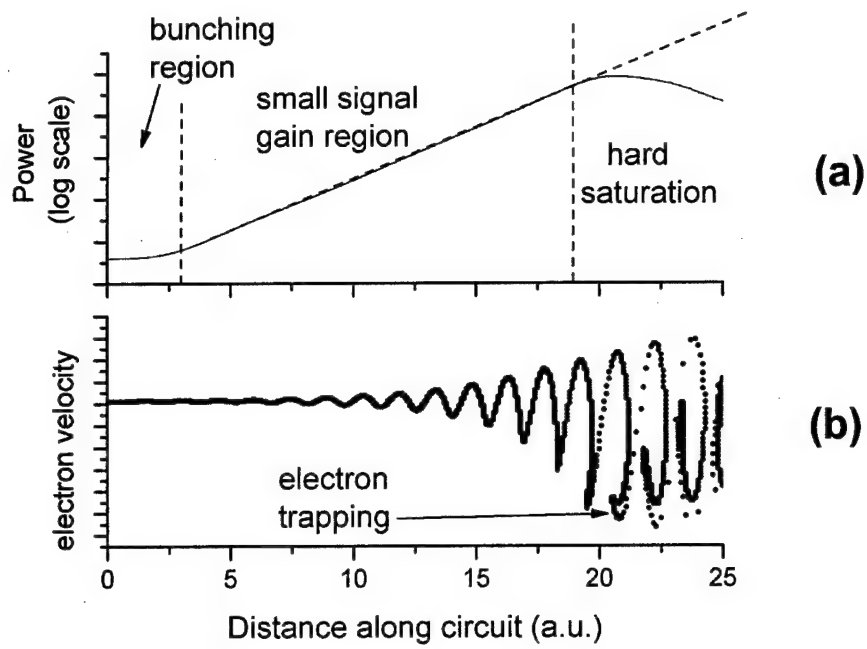

Fig. 8. Illustrations of (a) circuit wave power and (b) electron velocity evolution from a TWT simulation using the LMSUITE of open source codes available for teaching and research. Classic electron "particle trapping" responsible for saturation is illustrated by comparing figures (a) and (b). Movies of the evolution of these and other physical parameters (voltage, density, current) are available.

I.3. UW students

Student	Type and Date of Degree	Project Title	Status
John Wöhlbier	Ph.D. March 2003	Nonlinear Distortion and Suppression in Traveling Wave Tubes: Insights and Methods	Director Fellow, Scientist, Los Alamos National Laboratory
Mark Converse*	Ph.D. April 2003	Investigation of the Mechanisms of Pulse Amplification in Helical Traveling Wave Tubes	Post-doc, University of Wisconsin
Antoine Choffrut	Passed PhD qualifier and thesis proposal exams	LINC architectures for linear TWT transmitters operating at high efficiency	Work in progress
Sudeep Bhattacharjee	Post-doctoral scholar	Folded waveguide TWTs for THz applications	Will finish in Aug 2004 and assume a faculty position at Indian Institute of Technology
Mark McNeely*	M.S. 2001	Evaluation of a Method for Forming Sheet-Electron-Beams from an Initially Round-Electron-Beam using Magnetic Quadrupoles	International professional engineering consultant
Mike Wirth	M.S. 2002	Techniques in Microfabrication of a 400 GHz Folded Waveguide Travelling Wave Tube	Job with Madison startup company
Mike Neumann	M.S. 2000	Initial Experimental Investigations of Intermodulation in a Klystron Amplifier	Engineer, Agilent
John Wohlbier	M.S. 2000	Modeling and Analysis of a Traveling Wave Tube Under Multitone Excitation	Continued studies with Ph.D.
Antoine Choffrut	M.S., 2001	LINC methods for Linearizing TWT Amplifiers	Continued studies with Ph.D.
Sean Gallagher	M.S., 2003	Techniques in Microfabrication of a 400 GHz Folded Waveguide Travelling Wave Tube	Job in non-VED industry
Won-Je Lee	M.S., 2003	Reentrant Rectangular Cavity Resonator Design for Millimeter Wave and THz regime Klystrons	Continuing graduate studies in MEMS area
Aarti Singh	M.S. 2004	Suppression of Nonlinear Multitone Products in a Traveling Wave Tube Amplifier	Continuing graduate studies in digital communications theory
Ning Zhang	M.S. 2004	Studies of novel structures for THz regime TWTs and BWOs	Continuing graduate studies in applied physics
Kevin McLaughlin	M.S. in progress	Hot phase velocity measurements in a TWT	In progress
Matt Genack	M.S. 2004	Novel folded waveguide circuits for mmwave and THz regime TWTs	U.S. Patent Office

John Welter	M.S. in progress	Microfabricated folded waveguide TWTs for mmwave and THz regimes	In progress, will join L3 Comm Electron Devices upon graduation
Chad Marchewka**	B.S.	Chaos in a TWT amplifier with external feedback	Graduate studies at MIT with Temkin vacuum electronics group
John Welter**	B.S., 2003	Intermodulation injection to linearize multitoned klystron	Continued graduate studies at UW
Sean Sengele**	B.S., in progress	Development of TWT software for education and research, TWT simulations for optimized velocity tapers	In progress
Jassem Shahrani	B.S., 2002	Klystron cavity measurements	Engineer in industry
Bonnie Shum	B.S., 2001	Klystron cavity simulations using MAGIC	Engineer in industry
Min Ki Choi	B.S., 2001	MVED Educational materials development	Graduate studies in applied physics
Hyun Moon	B.S., 2001	MVED Educational materials development	Graduate studies in applied physics
Jean Nguyen	B.S., 2003	Studies of TWT helix circuits using HFSS	Graduate studies in applied physics
Al Mashal**	B.S., in progress	Experimental studies of novel klystron cavities for THz regime applications	In progress
Paul Larsen**	B.S., in progress	Chaos in a driven TWT oscillator with external feedback	In progress
Adam Bush	B.S., in progress	Experimental studies of TWTs in LINC architectures for linear amplification at high efficiency	In progress

**** Industrial Intern with Northrop-Grumman, Rolling Meadows, IL***

***** Industrial Intern with L3-Communications ED, San Carlos, CA***

****** Note that two of UW's undergraduate MVE students have ended up at other MVE schools: Jim Anderson was an undergraduate student educated in our UW laboratory who went on to attend first the University of Maryland and then the MIT MVE groups. Chad Marchewka has finished his undergraduate studies in our laboratory in Fall 2003 and joined the MIT MVE group in January 2004.***

I.4. List of publications and presentations

I.4.1. Journal papers

1. "The Multifrequency Spectral Eulerian (MUSE) Model of a Traveling Wave Tube," J.G. Wöhlbier, J.H. Booske, I. Dobson, IEEE Trans. Plasma Science, 30 [3],1063-1075 (2002).

2. "Third-Order Intermodulation Reduction by Harmonic Injection in a TWT Amplifier," M. Wirth, A. Singh, J. Scharer, and J. Booske, IEEE Trans. Electron Devices, Vol. 49, No. 6, 1082 – 1084 (2002).

3. "TWT Linearization using LINC architecture," A. Choffrut, B. VanVeen, and J.H. Booske, IEEE Trans. Electron Devices, Vol. 50, No. 5, pp. 1405 – 1408 (2003).

4. "Generation and growth rates of nonlinear distortions in a traveling wave tube," J.G. Wöhlbier, I. Dobson, and J.H. Booske, PHYS REV E 66 (5): art. no. 056504, NOV 2002.

5. "Suppression of third-order intermodulation in a klystron by third-order injection," S. Bhattacharjee, C. Marchewka, J. Welter, R. Kowalczyk, C.B. Wilsen, J.H. Booske, Y.Y. Lau, M.W. Keyser, A. Singh, J.E. Scharer, R.M Gilgenbach, M.J. Neumann, Phys. Rev. Lett., vol. 90, No. 9, paper 098303, 4 pages (2003).

6. "An Eulerian method for computing multi-valued solutions of the Euler-Poisson equations and application to wave breaking in klystrons," Xiantao Li, John G. Wöhlbier, Shi Jin, and John H. Booske, Phys Rev. E, vol. 70, no. 7, paper 016502, 12 pages, (2004).

7. "Experimental Verification of the Mechanisms for Nonlinear Harmonic Growth and Suppression by Harmonic Injection in a Traveling Wave Tube," A. Singh, J. G. Wöhlbier, J. H.Booske, J. E. Scharer, Phys. Rev. Lett. Vol. 92, paper 205005 (2004).

8. "Insights from one-dimensional linearized Pierce theory about wideband traveling wave tubes with high space charge," J.H. Booske and M.C. Converse, IEEE Trans. Plasma Sci. (to be published, 2004).

9. "Mechanisms for phase distortion in a traveling wave tube," J.G. Wöhlbier and J.H. Booske, Phys. Rev. E, Vol. 69 [6], article 066502, 16 pages, (2004).

10. "On the physics of harmonic injection in a traveling wave tube,"J.G. Wöhlbier, J.H. Booske, and I. Dobson, IEEE Trans. Plasma Science, (to be published, 2004).

11. "Folded Waveguide Traveling Wave Tube Sources of THz Radiation," S. Bhattacharjee, J. H. Booske, D. W. van der Weide, C. L. Kory, S. Limbach, S. Gallagher, J.D. Welter, M. R. Lopez, R. M. Gilgenbach, R.L. Ives, M. E. Read, R. Divan, and D. C. Mancini, Trans. Plasma Sci. (to be published, 2004).

12. "Impulse Amplification in a Traveling Wave Tube I: Simulation and Experimental Validation," M.C. Converse, J.H. Booske, and S.G. Hagness, Trans. Plasma Sci (to be published, 2004)

13. "Impulse Amplification in a Traveling Wave Tube II: Large Signal Physics," M.C. Converse, J.H. Booske, and S.G. Hagness, Trans. Plasma Sci., (to be published, 2004)

14. "Improvements in Graphite-Based X-ray Mask Fabrication for Ultra-Deep X-ray Lithography," R. Divan, D.C. Mancini, S. M. Gallagher, J. Booske, and D. van der Weide, J. Microsystem Technologies (to be published, 2004).

15. "Minimizing Spectral Leakage of Non-Ideal LINC Transmitters by Analysis of Component Impairments," A. Choffrut, B.D. VanVeen, and J.H. Booske, IEEE Trans. Vehicular Technol. (submitted, 2004).

16. "Second and Third Order Signal Injection for Nonlinear Distortion Suppression in a Traveling Wave Tube," A. Singh, J. Scharer, J. Wöhlbier, and J. Booske, IEEE Trans. Elec. Devices (Submitted, 2004).

17. "Nonlinear Space Charge Wave Theory of Distortion in a Klystron," John G. Wöhlbier and John H. Booske, IEEE Trans. Elec. Devices (submitted, 2004).

In addition, at least two more papers (currently in preparation) are anticipated to be submitted for publication during 2004-2005 on the subjects of chaotic TWT transmitters and microfabricated folded waveguide TWTs for millimeter-wave and THz regime amplifiers.

I.4.2. M.S. and Ph.D. theses and reports

1. Mark C. Converse, "Investigation of the Mechanisms of Pulse Amplification in Helical Traveling Wave Tubes," Ph.D. Dissertation, UW-Madison (2003)

2. John G. Wöhlbier, "Nonlinear Distortion and Suppression in Traveling Wave Tubes: Insights and Methods," Ph.D. Dissertation, UW-Madison (2003).

3. John G. Wohlbier, "Modeling and Analysis of a Traveling Wave Tube Under Multitone Excitation," M.S. Thesis, UW-Madison (2000).

4. Sean Gallagher, "Techniques in Microfabrication of a 400 GHz Folded Waveguide Travelling Wave Tube," M.S. Report, UW-Madison (2003)

5. Won-Je Lee, "Reentrant Rectangular Cavity Resonator Design for Millimeter Wave and THz regime Klystrons," M.S. Report, UW-Madison, (2003)

6. Michael J. Wirth, "Experimental Investigations of a Custom Made Helical Traveling Wave Tube amplifier", M.S. Thesis, UW-Madison (2002)

7. Aarti Singh, "Suppression of Nonlinear Multitone Products in a Traveling Wave Tube Amplifier", M.S. Thesis, UW-Madison (2003).

8. Mark N. McNeely, "Evaluation of a Method for Forming Sheet-Electron-Beams from an Initially Round-Electron-Beam using Magnetic Quadrupoles," M.S. Project Report, UW-Madison (2001).

9. Michael J. Neumann, "Initial Experimental Investigations of Intermodulation in a Klystron Amplifier," M.S. Report, UW-Madison (2000).

10. Antoine Choffrut, "LINC methods for Linearizing TWT Amplifiers," M.S. Report, UW-Madison (2001).

11. Ning Zhang, "Conceptual Investigation and Performance Estimation of a THz Micro-Backward Wave Oscillator Circuit," M.S. Report, UW-Madison (2004).

12. Matt Genack, "The Effects of a Mid-Plane Broad Wall Gap on the Electromagnetic Properties of a Folded Waveguide," M.S. Report, UW-Madison (2004).

13. John Welter, "MEMs Microfabrication of THz TWTs and Millimeter-Wave TWT Components," M.S. Report, UW-Madison (to be completed, 2004).

14. Kevin McLaughlin, "Measurements of hot phase velocity and space charge reduction coefficient on a broadband TWT," M.S. Report, UW-Madison, (to be completed, 2005).

I.4.3. Conference papers and presentations

1. "Localized Growth Rates of Intermodulation Products in a Multitone Traveling Wave Tube Amplifier," J.G. Wohlbier, I. Dobson, J.H. Booske, and J.E. Scharer, The 26th IEEE International Conference on Plasma Science, Monterey, CA, 20-24 June, 1999.

2. "Analysis of 3D Phase Space Dynamics of Pencil-to-Sheet Electron Beam Transformation in Highly-Non-Paraxial Quadrupole Lens System," M.J. McNeely, J.H. Booske, J.E. Scharer, and M.A. Basten, The 26th IEEE International Conference on Plasma Science, Monterey, CA, 20-24 June, 1999.

3. "Simplified Model of a Multitoned Traveling Wave Tube Amplifier," J.G. Wöhlbier, J.H. Booske, I. Dobson, and J.E. Scharer, 41st Annual Meeting of Division of Plasma Physics, American Physical Society (Seattle, WA, Nov. 15-19, 1999).

4. "Traveling Wave Tube Amplifier (TWTA) Physics Using a Custom-Modified Experimental Test Device," M.M. McNeely, M.C. Converse, J.H. Booske, J.E. Scharer, G. Groshart, B. Gannon, 41st Annual Meeting of Division of Plasma Physics, American Physical Society (Seattle, WA, Nov. 15-19, 1999).

5. "Advanced Investigations of Traveling Wave Tube (TWT) Physics Using a Custom-Modified Experimental Test Device," M.M. McNeely, M.C. Converse, M.A. Wirth, J.H. Booske, J.E. Scharer, G. Groshart, B. Gannon, and C.M. Armstrong, 1st IEEE International Vacuum Electronics Conference, Monterey, CA, May 2-4, 2000.

6. "Investigations of nonlinearities and multitone response in a broad band, high gain, helix traveling wave tube amplifier," M.C. Converse, M.M. McNeely, J.H. Booske, J.E. Scharer, C.L. Kory, and D. Zavadil, 1st IEEE International Vacuum Electronics Conference, Monterey, CA, May 2-4, 2000.

7. "Multifrequency Beam-Wave Interaction in an Idealized Broadband Vacuum Microwave Amplifier Model," J.G. Wohlbier, I. Dobson, and J.H. Booske, 27th IEEE International Conference on Plasma Science, June 4-7, 2000, New Orleans, LA.

8. "Investigations of Non-Linear Spectral Behavior in Multi-Toned Traveling Wave Tube Amplifiers," M.A. Wirth, J.E. Scharer, J.H. Booske, M.C. Converse, M.M. McNeely, J.G. Wohlbier, G. Groshart, B. Gannon, and C.M. Armstrong, 27th IEEE International Conference on Plasma Science, June 4-7, 2000, New Orleans, LA.

9. "Nonlinear Characterization and comparison with simulation of a high gain, broad band helix traveling wave tube amplifier," MM McNeely, MC Converse, JH Booske, JE Scharer, CL Kory, and D Zavadil, 27th IEEE International Conference on Plasma Science, June 4-7, 2000, New Orleans, LA.

10. "Magnetron Simulations and Experiments," M.R. Lopez, R.M. Gilgenbach, S.A. Anderson, Y.Y. Lau, M.L. Brake, C.W. Peters, W.E. Cohen, R.L. Jaynes, J.W. Luginsland, T.A. Spencer, R.W. Lemke, D. Price, J.H. Booske, M.J. McNeely, and L. Ludeking, 27th IEEE International Conference on Plasma Science, June 4-7, 2000, New Orleans, LA.

11. "Investigation of Transients and Pulses in Traveling Wave Tubes," M.C. Converse, J.H. Booske, Y.Y. Lau, S.C. Hagness, M.M. McNeely, M.A. Wirth, J.E. Scharer, and C. Wilsen, 42nd Annual Mtg, Division of Plasma Physics, American Physical Society, November, 2000.

12. "Comparison of Four Multifrequency Traveling Wave Tube Models," J.G. Wöhlbier, I. Dobson, and J.H. Booske, 42nd Annual Mtg, Division of Plasma Physics, American Physical Society, November, 2000.

13. "New Nonlinear Multifrequency TWT Model," J.G. Wöhlbier, J.H. Booske, and I. Dobson, 2nd IEEE International Vacuum Electronics Conference, Huis ter Duin, Noordwijk, Netherlands, 2-4 April, 2001.

14. "Micromachined TWTs for THz Radiation Sources: Proposal and Simulation," J.H. Booske, D. van der Weide, C.L. Kory, S.T. Limbach, S.-J. Lee, S.M. Gallagher, P.J.

Gustafson, 2nd IEEE International Vacuum Electronics Conference, Huis ter Duin, Noordwijk, Netherlands, 2-4 April, 2001.

15. "Investigation of Ultrawideband Pulses in Wideband Helix Traveling Wave Tubes: Theory and Simulation," M. Converse, S.C. Hagness, J.H. Booske, M.M. McNeely, M.A. Wirth, J.E. Scharer, Y.Y. Lau, C. Wilsen, C.L. Kory, IEEE International Conference on Plasma Science, Las Vegas, NV, June 2001.

16. "Initial Experimental Investigations of Intermodulation in a Klystron Amplifier," M. Neumann, J.Booske, M. Wirth, J.E. Scharer, P.L. Shum, C. Wilsen, Y.Y. Lau, R.M. Gilgenbach, IEEE International Conference on Plasma Science, Las Vegas, NV, June 2001.

17. "LINC Transmission Using Traveling Wave Tubes," A. Choffrut, B. Van Veen, J. Booske, IEEE International Conference on Plasma Science, Las Vegas, NV, June 2001.

18. "Finite Bandwidth and Space Charge Effects in the MUSE model," J.G. Wöhlbier , J.H. Booske, and I Dobson, IEEE International Conference on Plasma Science, Las Vegas, NV, June 2001.

19. "Investigations of Nonlinear Spectral Behavior in Multi-toned Helix Traveling Wave Tubes," M. Wirth, J.E. Scharer, J.H. Booske, M.C. Converse, M.M. McNeely, G. Groshart, B. Gannon, C. Armstrong, IEEE International Conference on Plasma Science, Las Vegas, NV, June 2001.

20. "Terahertz Regime, Micro-VEDs: Evaluation of Micromachined TWT Conceptual Designs," J.H. Booske, C.L. Kory, D. Gallagher, V. Heinen, K. Kreischer, D. van der Weide, S. Limbach, P. Gustafson, W.-J. Lee, S. Gallagher, K Jain , IEEE International Conference on Plasma Science, Las Vegas, NV, June 2001.

21. "Investigations of Intermodulation in a Klystron Amplifier," M.J. Neumann, J.H. Booske, M.A. Wirth, J.E. Scharer, C. Wilsen, Y.Y. Lau, 43rd Annual Meeting of the American Physical Society's Division of Plasma Physics, Long Beach, CA (Oct 29 – Nov 2, 2001).

22. "Investigations of Non-linear Spectral Growth in a Broadband Traveling Wave Tube Amplifier," M.A. Wirth, J.E. Scharer, J.H. Booske, M.C. Converse, A. Singh, J.G. Wohlbier, and C. Armstrong, 43rd Annual Meeting of the American Physical Society's Division of Plasma Physics, Long Beach, CA (Oct 29 – Nov 2, 2001).

23. "Microfabricated TWTs as high power, wideband sources of THz radiation, " J.H. Booske, W.-J. Lee, S. Gallagher, D. van der Weide, S. Limbach, K. Jain and C.L. Kory, Proceedings of the 9th International Conference on Terahertz Electronics, (Charlottesville, VA, 15-16 October, 2001).

24. "New Opportunities in Vacuum Electronics Using Microfabrication Technologies", J.H. Booske, Third IEEE International Vacuum Electronics Conference, April 23-25, 2002, Monterey CA, USA. **Plenary Talk**

25. "Comprehensive Simulations of Compact THz Radiation Sources Using Microfabricated Folded-Waveguide TWTs," S. Bhattacharjee, W.-J. Lee, S. Gallagher, D.W. van der Weide, J.H. Booske, S. Limbach, 3rd IEEE International Vacuum Electronics Conference, (Monterey, CA, 23-25 April, 2002).

26. "Hot phase velocity measurements and modeling for a broad-band TWT," M. Converse, A. Singh, J. Scharer, M. Wirth, S. Bhattacharjee, J. Booske, C. Armstrong, 3rd IEEE International Vacuum Electronics Conference, (Monterey, CA, 23-25 April, 2002).

27. "The Physics of Harmonic Injection in a TWT," J.G. Wöhlbier, J.H. Booske, I. Dobson, 3rd IEEE International Vacuum Electronics Conference, (Monterey, CA, 23-25 April, 2002).

28. "Intermodulation Suppression in a Broadband TWT," A. Singh, J. Scharer, M. Wirth, S. Bhattacharjee, J. Booske, 3rd IEEE International Vacuum Electronics Conference, (Monterey, CA, 23-25 April, 2002).

29. "Effects of Modulator Misalignment on LINC Transmission with TWT Amplifiers," A. Choffrut, B.D. Van Veen, J.H. Booske, 3rd IEEE International Vacuum Electronics Conference, (Monterey, CA, 23-25 April, 2002).

30. "THz radiation using high power, microfabricated, wideband TWTs," C. L. Kory, J. H. Booske, W.-J. Lee, S. Gallagher, D. W. van der Weide, S. Limbach, and S. Bhattacharjee, Proceedings of the 2002 IEEE MTT-S International Microwave Symposium, Seattle, WA, June 2-7, 2002.

31. "An Eulerian method for computing multi-valued solutions of the Euler-Poisson equations," X. Li, J. Wöhlbier, S. Jin, J. Booske, Annual Meeting of the Division of Plasma Physics, American Physical Society, Orlando, FL, Nov. 11-15, 2002.

32. "Investigation of Various Techniques for Intermodulation Suppression in a TWT amplifier," A. Singh, J. Scharer, M. Wirth, S. Bhattacharjee, and J. Booske, Annual Meeting of the Division of Plasma Physics, American Physical Society, Orlando, FL, Nov. 11-15, 2002.

33. "The Physics of Phase Nonlinearity in a Traveling Wave Tube," J. Wöhlbier, J. Booske, I. Dobson, Annual Meeting of the Division of Plasma Physics, American Physical Society, Orlando, FL, Nov. 11-15, 2002.

34. "A compact folded waveguide traveling wave tube oscillator for the generation of Terahertz radiation," S. Bhattacharjee, J.H. Booske, W.-J. Lee, C.L. Kory, S.

Gallagher, M. Genack, S. Limbach, M.R. Lopez, R.M. Gilgenbach, Annual Meeting of the Division of Plasma Physics, American Physical Society, Orlando, FL, Nov. 11-15, 2002.

35. "THz Radiation using Compact Folded Waveguide TWT Oscillators," S. Bhattacharjee, J. H. Booske, C. L. Kory, D. W. van der Weide, S. Limbach, M. Lopez, R. M. Gilgenbach, S. Gallagher, A. Stevens, and M. Genack, IEEE MTT-S International Microwave Symposium, Philadelphia, June 8-13, 2003.

36. "LATTE/MUSE Numerical Suite: An open-source teaching and research code for traveling wave tube amplifiers," J.G. Wöhlbier, M.C. Converse, J. Plouin, A. Rawal, A. Singh, and J.H. Booske, 30th IEEE International Conference on Plasma Science, Jeju, Korea, June 2-5, 2003.

37. "Experimental observation and characterization of chaos in a driven TWT oscillator with delayed feedback," S. Bhattacharjee, C. Marchewka, J. H. Booske, and J.E. Scharer, 30th IEEE International Conference on Plasma Science, Jeju, Korea, June 2-5, 2003.

38. "Folded Waveguide Traveling Wave Tube Sources of THz Radiation," S. Bhattacharjee, J. H. Booske, D. W. van der Weide, C. L. Kory, S. Gallagher, A. Stevens, M. Genack, M. Lopez, R. M. Gilgenbach[2], J. Wöhlbier, S. Limbach, R.L. Ives, M. E. Read, 30th IEEE International Conference on Plasma Science, Jeju, Korea, June 2-5, 2003.

39. "Injection schemes for TWT linearization" A. Singh, J.G. Wöhlbier, J.E. Scharer and J.H. Booske, 30th IEEE International Conference on Plasma Science, Jeju, Korea, June 2-5, 2003.

40. "Investigations of Folded Waveguide TWT Oscillators for THz Radiation," S. Bhattacharjee, J.H. Booske, C.L. Kory, D.W. van der Weide, S. Limbach, S. Gallagher, A. Stevens, M. Genack, J. Welter, M. Lopez, R.M. Gilgenbach, J. Wöhlbier, R.L. Ives, M.E. Read, R. Divan, D.C. Mancini, 4th IEEE Intl. Vacuum Electronics Conference, Seoul, Korea, May 28-30, 2003. **Invited Talk**

41. "LATTE/MUSE Numerical Suite: An Open Source Teaching and Research Code for Traveling Wave Tube Amplifiers," J.G. Wöhlbier, M.C. Converse, J. Plouin, A. Rawal, A. Singh, and J.H. Booske, 4th IEEE Intl. Vacuum Electronics Conference, Seoul, Korea, May 28-30, 2003.

42. "Experimental observation and characterization of chaos in a driven TWT amplifier with Delayed feedback," S. Bhattacharjee, C. Marchewka, J.H. Booske, and J.E. Scharer, 4th IEEE Intl. Vacuum Electronics Conference, Seoul, Korea, May 28-30, 2003.

43. "Injection schemes for TWT linearization," A. Singh, J.G. Wöhlbier, J.E. Scharer, and J.H. Booske, 4th IEEE Intl. Vacuum Electronics Conference, Seoul, Korea, May 28-30, 2003.

44. "A New View of Phase Distortion in a Traveling Wave Tube," J.G. Wöhlbier, J.H. Booske, and I. Dobson, 4th IEEE Intl. Vacuum Electronics Conference, Seoul, Korea, May 28-30, 2003.

45. "Investigations of Ultrawideband Pulses in Wideband Helix Traveling Wave Tubes," M.C. Converse, J.H. Booske, S.C. Hagness, and J. Wöhlbier, 4th IEEE Intl. Vacuum Electronics Conference, Seoul, Korea, May 28-30, 2003.

46. "Experimental observation and characterization of chaos in a driven TWT oscillator with delayed feedback," S. Bhattacharjee, C. Marchewka, J. H. Booske, and J.E. Scharer, 30th IEEE International Conference on Plasma Science, Jeju, Korea, June 2-5, 2003.

47. "Folded Waveguide Traveling Wave Tube Sources of THz Radiation," S. Bhattacharjee, J. H. Booske, D. W. van der Weide, C. L. Kory, S. Gallagher, A. Stevens, M. Genack, M. Lopez, R. M. Gilgenbach[2], J. Wohlbier, S. Limbach, R.L. Ives, M. E. Read, 30th IEEE International Conference on Plasma Science, Jeju, Korea, June 2-5, 2003.

48. "Injection schemes for TWT linearization" A. Singh, J.G. Wöhlbier, J.E. Scharer and J.H. Booske, 30th IEEE International Conference on Plasma Science, Jeju, Korea, June 2-5, 2003.

49. "A new look at the nonlinear physics of Traveling Wave Tubes," J.G. Wohlbier, J.H. Booske, I. Dobson, A. Singh, and J.E. Scharer, 45th Ann. Mtg of Amer. Phys. Soc. Division of Plasma Phys, (Albuquerque, NM, Oct 27-31, 2003).

50. "Experimental observation and characterization of chaos in a driven TWT amplifier with delayed feedback," S. Bhattacharjee, C. Marchewka, J. Booske, 45th Ann. Mtg of Amer. Phys. Soc. Division of Plasma Phys, (Albuquerque, NM, Oct 27-31, 2003).

51. "Generation of chaotic radiation in a driven TWT amplifier with delayed feedback", C. Marchewka, P. Larsen, S. Bhattacharjee, J. H. Booske, N. M. Ryskin, V. N. Titov, 5th IEEE Intl. Vacuum Electronics Conference, Monterey, CA, April 27-29, 2004.

52. "Measurements of microwave electrical characteristics of folded waveguide circuits," M. Genack, S. Bhattacharjee, J.Booske, C. Kory, S.-J. Ho, D. van der Weide, L. Ives, M. Read, 5th IEEE Intl. Vacuum Electronics Conference, Monterey, CA, April 27-29, 2004.

53. "A modal description of intermodulation injection in a klystron," J.G. Wöhlbier and J.H. Booske, 5th IEEE Intl. Vacuum Electronics Conference, Monterey, CA, April 27-29, 2004.

54. "Sensitivity of Harmonic Injection and its Spatial Evolution for Nonlinear Distortion Suppression in a TWT," A. Singh, J.E. Scharer, J.G. Wöhlbier, and J.H. Booske, 5th IEEE Intl. Vacuum Electronics Conference, Monterey, CA, April 27-29, 2004.

55. "MEMS-Microfabricated Components for Millimeter-Wave and THz TWTs," John Welter, John Booske, Hongrui Jiang, Sudeep Bhattacharjee, Steve Limbach, Dan van der Weide, Ning Zhang, John Scharer, Matt Genack, and Al Mashal, Carol Kory, Lawrence Ives, Mike Read, 5th IEEE Intl. Vacuum Electronics Conference, Monterey, CA, April 27-29, 2004.

56. "Phase Velocity Measurements on a Broadband TWT," K.G. McLaughlin, J.H. Booske, and J.E. Scharer, 31st IEEE International Conference on Plasma Science, June 28 – July 1, Baltimore, MD (2004)

57. "Sensitivity of Harmonic Injection and its Spatial Evolution for Nonlinear Distortion Suppression in a TWT," A. Singh, J.E. Scharer, J.G. Wohlbier, and J.H. Booske, 31st IEEE International Conference on Plasma Science, June 28 – July 1, Baltimore, MD (2004).

58. "Synchronization and Generation of Chaos in a Driven TWT Amplifier with Delayed Feedback," C. Marchewka, P. Larsen, S. Bhattacharjee, J.H. Booske, N.M. Ryskin, and V.N. Titov, 31st IEEE International Conference on Plasma Science, June 28 – July 1, Baltimore, MD (2004).

I.4.4. Publicity

Feature Story on Madison ABC Affiliate Channel 27 evening news, "DoD-sponsored Research at the UW-Madison helps save lives of soldiers in the battlefield," Thursday, March 20, 2003.

Feature Story on Wisconsin Public Radio News, "DoD-sponsored Research at the UW-Madison could help improve radar jamming," Friday, April 4, 2003.
http://clipcast.wpr.org:8080/ramgen/wpr/news/news030404gh.rm

II. AFOSR FINAL REPORT: UNIVERSITY OF MICHIGAN

II.1. Overview

U-Michigan graduate students and faculty have made a major breakthrough by discovery of an innovative technique to dramatically reduce the noise in magnetron oscillators (2 patent applications filed). The technique utilizes an azimuthally-varying axial magnetic field. Microwave measurements show dramatic reductions in the noise of kW oven magnetrons operating near 2.45 GHz. The noise reduction near the carrier is some 30 dB. Microwave sidebands are reduced or eliminated. Noise reduction occurs at all anode currents, but is particularly significant at low current near the start-oscillation condition. Further, this technique has been shown to be effective in noise reduction regardless of the magnetron current or age. Magnetic-Priming of magnetrons in the pi-mode has been discovered by use of N/2 magnetic perturbations (where N is the number of magnetron cavities).

U-Michigan solved a 90-year old problem by finding a 2-dimensional Child-Langmuir Law, which gave the maximum current density that can be emitted over a finite patch of the cathode surface before the onset of a virtual cathode.

U-Michigan developed a general theory that accurately evaluates the Intermodulation products in a multi-cavity klystron that result from an input signal with multiple frequency components. The UM code has been validated with a series of collaborative experiments with our partner, U of Wisconsin. Also with UW, a novel method, by injecting a weak-signal, to suppress 3rd order intermod has been demonstrated.

U-Michigan quantified to what extent a thin film of contaminants would lead to excessive heating of high power rf windows, by a scaling law. The U Michigan scaling law surprisingly predicts that a thin film of contaminants (<< skin depth) may absorb up to a 50 percent of incident rf power.

II.2. Significant achievements

II.2.1. Magnetron noise reduction

This is a breakthrough of first magnitude. A novel, simple, low-cost, and effective method was discovered whereby noise in kW magnetron was suppressed. Two patent applications are being filed. Noise in crossed-field devices is an outstanding problem that defies cure. Very significant effort, in experimentation and in modeling, has been put forth by DoD in the last 15 years to reduce the noise in crossed-field amplifiers. These amplifiers are used in the Patriot and Aegis radars. Despite the heroic effort by the who's-who in crossed-field devices, no practical solution on CFA noise has emerged.

The UM work in this AFOSR-sponsored MVE program offered an innovative approach. Instead of studying the CFA directly, we provided an in-depth study of noise in the ubiquitous microwave oven magnetron. U-Michigan discovered a simple way to completely eliminate both the close-in and the sideband noise. It is expected that this

novel technique of noise reduction may be extended to DoD crossed-field amplifiers, as CFA and magnetrons share many similarities in the noise characteristics.

U-Michigan also discovered that the startup of the magnetron may be hastened, especially when N/2 magnetic periods are utilized, where N is the number of magnetron cavities. These results have been demonstrated for both new and old kW magnetrons. No significant degradation in power or efficiency is observed. It is expected that this novel technique of noise reduction may be extended to DoD crossed-field amplifiers, as CFA and magnetrons share many similarities in the noise characteristics. This invention is also expected to have far reaching consequences on reducing magnetron interference with communications systems that operate in the unlicensed 2.4 GHz spectrum (e.g., cordless phones, Bluetooth), extremely close to the 2.45 GHz oven frequency. Our newly discovered noise-reduction technique may also be applied to magnetrons used for homes, industrial heating and lighting. Multiple publications, Invited Talks (IVEC, ICOPS), Press Releases (APS, ABCnews.com, AIP, etc.), TV and radio interviews have covered this unprecedented advance. **A patent application was filed: "Low Noise, Crossed-Field Devices Such as a Microwave Magnetron Having an Azimuthally-Varying Axial Magnetic Field and Microwave Oven Utilizing Same"**

II.2.2. Analytic theory of higher dimensional Child-Langmuir law

For 90 years, there has been no useable analytic theory of Child-Langmuir Law beyond 1-D. Without exception, all 2D theories are very complicated; the results are neither transparent nor useable. However, a simple analytic 2D theory is of fundamental interest because electron emission is often restricted to finite patches on the cathode surface. Moreover, modern cathodes, such as ferroelectric cathodes, laser-triggered cathodes, and field emitter arrays, etc., have at times displayed the puzzling phenomenon that the emission current densities are higher than that predicted by the familiar 1D Child-Langmuir law. There is thus a pressing need for the development of a 2D Child Langmuir Law.

Answering this need, U Mich developed such a simple scaling law. It gives the maximum current density that can be emitted over a finite patch of the cathode surface before the onset of a virtual cathode. The theory is simple and elegant, developed from first principles. It has been shown to agree with simulation results. Immediately after its publication, this scaling law was used by NRL scientists to successfully interpret the current measured from their hibachi cathode on ELECTRA [Hegelar et al., Phys. Plasmas, 9, 4309, (2002)]. This work stimulated many studies elsewhere.

II.2.3. . First theory of klystron intermodulation

U Mich developed a general theory that accurately evaluates the intermodulation products which result from an input signal with multiple frequency components. In high power amplifiers, these IM products may reach unacceptable levels, thereby distorting the information being transmitted. This problem is acute for demanding modern analog and digital communications applications.

Prior to this work, virtually all large signal klystron simulation codes treated only single tone input signals. One basic problem in the development of a multi-signal klystron code is that of resolving the narrow spacing of the IM products from the carriers. Our newly developed algorithm got rid of this difficulty. It was also able to accurately account for charge overtaking and the space charge effects. The code has been validated with a series of collaborative experiments with our partner, U of Wisconsin. Also with UW, a novel method, by injecting a weak signal, to suppress 3-rd order intermod has been demonstrated. Calculations have been performed, using our newly developed klystron intermod code, to interpret this U Wisconsin experiment on intermod suppression. This joint UW-UM collaboration was published in Physical Review Letters.

Because of this work, and of his pioneering simulation studies in beam loading, U Mich graduate student Craig Wilsen received the IEEE Outstanding Graduate Student Award. These works were documented in his Ph.D. thesis.

The advance of the multi-signal code, its demonstrated ability to account for charge-overtaking, plus our work on beam-loading of cavities, are being applied to the multi-beam klystron (MBK) by U Mich student Richard Kowalczyk. MBK is now actively pursued at NRL. In fact, Dr. Baruch Levush of NRL has already approached U Mich PI's in having Richard Kowalczyk to do an internship at NRL on the multibeam klystron. Richard Kowalczyk already performed an internship at L-3 on this topic.

II.2.4. Heating of thin film on microwave windows

The extent to which a thin film of contaminants would lead to excessive heating of high power rf windows has never been quantified, in particular in terms of a scaling law. U Mich investigators provided such a scaling law, which surprisingly predicts that a thin film of contaminants (even much thinner than the skin depth) may absorb up to a 50 percent of the incident rf power. It also provides a novel scaling law for the resulting temperature rise. When this new result was presented to our industrial partner, Northrop-Grumman/Litton (now L3), in August, 2002, Dr. Al Theiss excitedly announced to the audience that this theory might explain the unexpected window failure that occurred significantly below the rated power. Note that this window failure has long been a puzzle (and worry) to Northrop-Grumman/ Litton/ L-3, which are heavily sponsored by DoD. Our work also stimulated Dr. Howard Jory of CPI to perform measurements on one of his broken diamond windows.

Thin film heating is of significant interest to DoD's HPM program. Thin film coatings of conductive materials with low secondary electron emission (SEE) yields, such as Ti, TiN or Cr_2O_3, are often deposited on the windows to prevent the occurrence of multipactor. Too-thin a film may not suppress SEE, whereas too-thick a film may lead to excessive Ohmic heating. The scaling laws mentioned above then provide a guide for the optimization of the film thickness, in particular when the film thickness is in the nanometer range.

II.2.5. Theory of crossed-field electron flow

The maximum injection current in an insulated, relativistic diode has been computed for the first time. Surprisingly, the space-charge limited condition is not the limiting condition. This finding was confirmed by MAGIC code simulations. Fundamental properties of cycloidal crossed-field flows were examined. The multiplicity of the solutions among the n-th order Slater orbits and the Brillouin flow is clarified. It is concluded that ALL Slater orbits are either highly unstable or simply physically inaccessible. The most probable state in a crossed-field diode is the Brillouin flow superimposed by a weak turbulent background. These statements hold regardless of the diode voltage (i.e., relativistic or not, as long as the diode is magnetically insulated).

II.2.6. Injection locking of magnetrons

A reflection amplifier system was constructed, similar to that employed by Brown. The oscillator magnetron was directed through a circulator and a tuning stub section to a matched load. The tuning stubs are utilized as a high power splitter, to reflect a portion of the microwave power. The circulators direct the reflected microwave power into a second magnetron, which acts as the amplifier. Another circulator is used to avoid reflections into the oscillator magnetron, to avoid frequency pulling. Microwave power and spectrum are monitored at appropriate points in the system corresponding to oscillators and amplifier. Initial experiments were performed to verify magnetron operation as a reflection amplifier.

These experimental data were compared with Adler's equation: the amplifier frequency corresponds exactly to the oscillator (drive) frequency for power levels above 10 W, in good agreement with Adler's equation. Furthermore, the magnetron's microwave output power scales linearly versus drive power above the level predicted by Adler's equation.

A major focus of this research program has been the identification of the "quiet" versus "noisy" state of magnetrons. These states are believed to hold the keys to the understanding of crossed-field noise. The quiet state was achieved by operating the magnetron with the heater turned off after the full microwave power was achieved. Note that the effect of the magnetic perturbations was to reproduce the quiet microwave spectrum from a magnetron.

II.3. U. Michigan graduate students

Student	Type and Date of Degree	Dissertation Title	Status
Craig Wilsen	Ph.D. 2001	Theory of Intermodulation in HighPower Microwave Amplifiers	Engineer: L-3
V. Bogdan Neculaes	Ph.D. Expected 2004	Low-Noise Magnetrons	UMi Grad Student
Richard Kowaczyk	Ph.D. Expected 2005	Design Studies of Multi-Beam Klystrons	UMi Grad Student (DoE Fellowship) L-3 Summer Intern
Herman Bosman	Expected Ph.D. 2004	Theory of RF Window Failure	UMi Grad Student (DoE Support)
Nick Jordan	Ph.D. Expected 2007	Magnetron Experiments & Simulation	UMi Grad Student L-3 Summer Intern
P. Pengvanich	Ph.D. expected 2007	Magnetron Theory	UMi Grad Student
Wilkin Tang	Ph.D. expected 2008	RF Heating of Window Contaminants	UMi Grad Student DoE Support L-3 Summer Intern
Michael Jones	Ph.D. expected 2005	Magnetron Simulation and Experiments	UMi Grad Student AFOSR support

II.4. List of publications and presentations

II.4.1. Patent application filed

"Low Noise, Crossed-Field Devices Such as a Microwave Magnetron Having an Azimuthally-Varying Axial Magnetic Field and Microwave Oven Utilizing Same"

II.4.2. Publications

1. M.C. Jones, V.B. Neculaes, W. White, Y.Y. Lau, and R.M. Gilgenbach, "Simulation of rapid startup in microwave magnetrons with azimuthally varying axial magnetic fields", Applied Physics Letters, 84, p1016, (2004).
2. "Limiting Current in a Relativistic Diode Under the Condition of Magnetic Insulation", M. Lopez, Y.Y. Lau, R.M. Gilgenbach, D.W. Jordan, J.W. Luginsland, Physics of Plasmas, 10, 4489, (2003)
3. "Low-noise microwave magnetrons by azimuthally varying axial magnetic field", V.B. Neculaes, R.M. Gilgenbach, and Y.Y. Lau, Applied Physics Letters, 83, p1938 (2003).
4. "Suppression of Third Order Intermodulation in a Klystron by Third Order Injection", S. Bhattacharje, C. Marchewka, J. Welter, R. Kowaczyk, C.B. Wilsen, Y.Y. Lau, J.H. Booske, A. Singh, J.E. Scharer, R.M. Gilgenbach, M.J. Neumann, and M.W. Keyser, Phys. Rev. Letters 90 (2003) March 7
5. "Microwave Absorption in a Thin Film", H. Bosman, Y.Y. Lau, R.M. Gilgenbach, Applied Physics Letters, 82 1353 (2003) MARCH
6. "A simulation study of beam loading on a cavity", C. Wilsen, J. Luginsland, Y.Y. Lau, T.M. Antonsen, D.P. Chernin, P.M. Tchou, M.W. Keyser, R.M. Gilgenbach, and

L.D. Ludeking, IEEE Trans. Plasma Science, Special Issue on High Power Microwaves, 30, p1160, 2002

7. A Note on Current Modulation from Nonlinear Electron orbits", C.B. Wilsen, Y.Y. Lau, D. Chernin, and R.M. Gilgenbach, IEEE Transaction on Plasma Science, Special Issue on High Power Microwave Generation, 30, p1176, 2002
8. "Single Surface Multipactor on a Dielectric Surface", R. Anderson, W. Getty, M.L. Brake, Y.Y. Lau, R.M. Gilgenbach, and A. Valfells, Review of Scientific Instruments, 72, 3095 (2001).
9. Theory of Intermodulation of a klystron", Y.Y. Lau, D.P. Chernin, C. Wilsen, and R.M. Gilgenbach, IEEE Trans. Plasma Science, 28 959 June (2000)
10. Y. Y. Lau, "A simple theory on the two-dimensional Child-Langmuir Law", Phys. Rev. Lett. 87, (Dec. 10, 2001 issue).
11. J. W. Luginsland, Y. Y. Lau, R. J. Umstattd, and J. J. Watrous, "Beyond the Child Langmuir Law: The Physics of Multi-Dimensional Space-Charge-Limited Emission", Phys. Plasmas, 2002

II.4.3. Student conference call presentations

1. Mike Lopez, UM, presented at main MVE MURI99 Teleconference
2. Herman Bosman, UM, presented at MVE MURI99 Student Teleconference
3. Bogdan Neculaes, MVE MURI99 Teleconference: "Low Noise Magnetron by Azimuthally Varying Axial Magnetic Field"